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INFLATABLE SOLAR SAILS FOR LOW-COST ROBOTIC MARS MISSIONS

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ABSTRACT

This paper presents an evaluation of the use of solar sails based on inflatable-structures technologies to perform low-cost robotic planetary missions. We show that there is a significant potential synergism between the emerging technologies of microspacecraft and inflatable solar sails that offer the unique capability of performing planetary science missions using a small, low-cost launch vehicle, such as the Pegasus XL, with a launch cost of less than $25M. In the example evaluated here, a roughly 100-m diameter inflatable solar sail can deliver a 48-kg rnicrospacecraft payload to Mars orbit with a trip time of about 725 days. Once in orbit, the microspacecraft can perform orbit changes (including atmospheric entry) with no expenditure of propellant by using the solar sail.

INTRODUCTION

Solar sails operate by using momentum exchange with solar photons; this amounts to a force of 9 Newtons/km^2 at 1 AU. As such, a solar sail has "infinite" specific impulse (I_{sp}), because it requires no propellant, but it does have a low acceleration resulting in long trip times. Also, solar sails are typically large, gossamer structures with dimensions of hundreds of meters to kilometers.

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Solar sails were first extensively studied in the late 1970's for the Halley Comet rendezvous mission. [1] At that time, detailed analyses were made of solar sail fabrication techniques (thin silvered sheets and light-weight booms), control and dynamics, and trajectory analyses. The study found that solar sails were eminently feasible from a technology and mission performance point of view, but the development risk was considered too high for the short time available before launch. Instead, Solar Electric Propulsion (SEP) was considered less risky given the mission's schedule constraints.

Although the Halley Comet mission was not pursued by the United States, interest in solar sails for a variety of lunar and Mars cargo missions, as well as planetary missions, were continued at a low level because solar sails represent the most fuel efficient possible inter-orbital "supertanker" in space. Solar sails have been extensively studied in the past for Mars cargo missions; much of the discussions below are derived from these studies.[2,3,4,5]

Figure 1 illustrates three solar sail concepts. The square and heliogyro sails represent the "classic" sail designs considered by the Halley Comet mission studies and various subsequent mission studies; the inflatable sail concept is a recent innovation derived from inflatable optics/structures technology. The "classic" square sail consists of a thin (few mills) sheet of silvered or aluminized plastic stretched over a supporting light-weight boom. Small "fly swatter" vanes are located at the comers of the sail; they have a combined area of 0.5% of the total sail area and are rotated to produce differential light pressure for use in maneuvering the sail.[3] The sail can also be maneuvered by shifting the payload so that the center of mass is offset from the center of (light) pressure. A private organization, the World Space Foundation, has built a prototype square sail (880 m^2 area) as a demonstration of the required on-orbit deployment and maneuvering capability. The group is awaiting a launch vehicle to place the sail in a high-altitude orbit, because a sail cannot operate below an altitude of about 2000 km due to air drag would exceeding photon pressure at a lower altitude.[5]

The second type of "classic" sail illustrated in Figure 1 is the heliogyro solar sail. In this concept, the sail is spun like a helicopter blade; the thin-sheet sail material is unrolled and stabilized by centrifugal force. Maneuvering is accomplished by changing the "pitch" of the blades. The heliogyro sail is easier to deploy than the square sail; has a greater stability from random disturbances (due to its rotational inertia), but has a slower maneuvering rate due to the rotational inertia.[1] Thus, the two types of sails have different strengths and weaknesses, although the square sail, with its faster maneuvering (turning) response, might be favored for missions involving extensive planetary escape and capture spiral orbits (because the sail has to re-orient itself relative to the sun on each orbit).

Recently, it has been proposed[6] that a new type of solar sail could be developed based on advances on inflatable structures technology. As shown in Figure 1, this sail is similar to the square sail in that it does not rotate, but instead of using deployable booms for structural rigidity, it uses an inflatable torus to support the thin-sheet sail material, and inflatable booms for payload attachment. As with the square sail, attitude control could be achieved through the use of small "fly swatter" vanes or by shifting the payload mass relative to the center of (light) pressure.

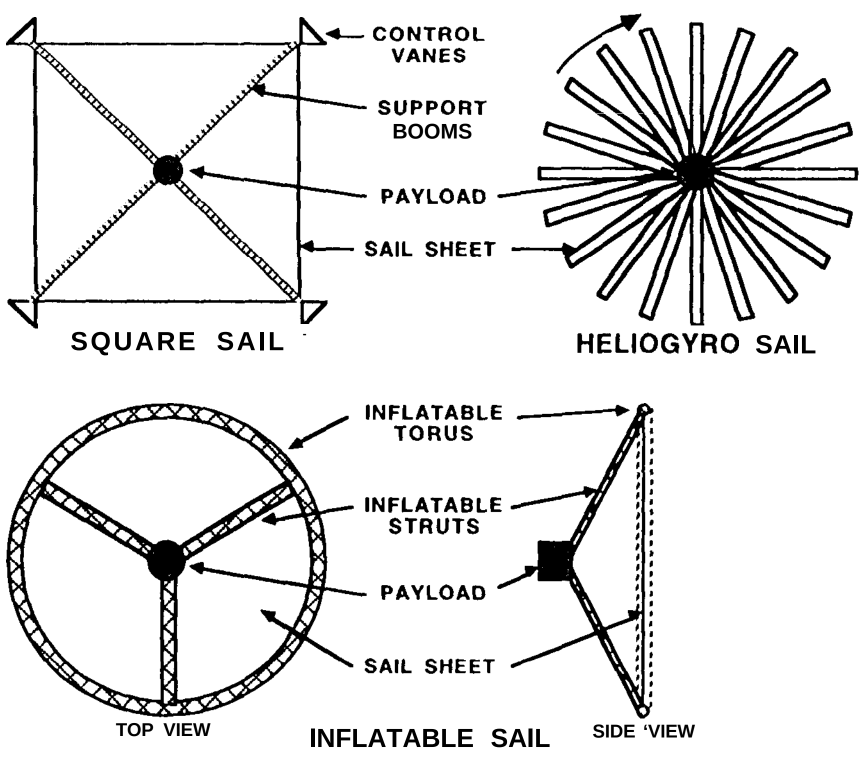

Figure 1. Solar Sail Concepts

MISSION ANALYSIS ASSUMPTIONS

Historically, mission studies of solar sails have concentrated on the use of large sails (e.g., with areas on the order of 1 to 4 km^2) for robotic high-AV science missions or as interplanetary cargo "supertankers" in support of piloted Mars missions. In the mission analysis presented below, we determined the mission performance of a Mars robotic science mission in which a relatively small solar sail is used to transport a small or micro-spacecraft from Earth to Mars orbit. Once in its final orbit, the spacecraft could perform various mapping and remote sensing experiments. Alternatively, the sail could use aerodynamic drag to slowly aerobrake into a lower altitude and eventually de-orbit the spacecraft for landing (analogous to the orbit-changes performed by the Magellan spacecraft at Venus). Finally, as shown below, the combination of microspacecraft and solar sails technologies offers the unique capability of performing planetary science missions using a small, low-cost launch vehicle such as the Pegasus XL, with a launch cost of less than $25M.

Solar Sail Areal Density

The primary performance parameter for solar sails is their areal density (grams/m^2). This parameter is an important measure of sail performance because it determines the acceleration of the sail (i.e., solar pressure [N/km^2] divided by areal density [g/m^2] gives acceleration). Area] density, in turn, is determined by both the thickness of the sail sheeting and the supporting structure (e.g., booms or inflatable torus, etc.). For example, in the Halley Comet mission and more recently in studies by Staehle on sails for Mars cargo missions,[2] deployable square thin-sheet sails were assumed with a total areal density (sail sheet plus structure) of 5 g/m^2. A deployable sail requires relatively thick sail sheet (e.g., 2.5-micron thick Kapton) to survive folding (on the ground) and packing into a launch vehicle, followed by unfoldirg (deployment) on orbit. By contrast, Garvey[3] and Drexler[7] have considered thin-sheet sails erected or constructed (fabricated) on orbit; because these sails do not need to be folded/unfolded, the sheet can be much thinner (e.g., 0.015 to 0.2-microns thick). This results in sails which are erected or fabricated on-orbit with areal densities ranging from 1.0 g/m^2 (Garvey) to less than 0.3 g/m^2 (Drexler). Thus, a Garvey - or Drexler-type sail could have significantly higher acceleration, and thus shorter trip time, than a deployable Staehle-type sail. For a given area, the Staehle-type sail would also be significantly heavier. However, this must be balanced against the infrastructure requirement of a sail erection/fabrication facility in orbit. This facility would basically be a separate space station,3 whose mass would have to be included in the total initial mass in low Earth orbit (IMLEO) for the advanced sails.

For an inflatable structures sail based on inflatable optics technology, estimates of the areal density range from around 70 g/m2 for "mirrors" with diameters on the order of 10 m, to 12 g/m^2 for systems with diameters on the order of kilometers.[6] Interestingly, as shown in Figure 2, there is a minimum in the areal density of 8 g/m^2 for inflatable sails with dimensions on the order of 100 m. This minimum occurs because small-diameter inflatable sails suffer from torus manufacturing constraints which limit the torus to a cross-section diameter of 2.5 cm, whereas sails with diameters larger than 100 m have a large torus that must be strengthened to survive buckling loads. As will be shown in the mission analysis section below, the inflatable solar sail diameters of interest to this mission range in diameter from around 100 to 130 m. Thus, the mission requirement results in a sail diameter that fortuitously falls in a region where the sail areal density is at a minimum of 8 g/m^2.

Solar Sail Packaged Volume

Figure 3 illustrates the pre-deployment volume of inflatable solar sails as a function of their final diameter.[6] As discussed below, this

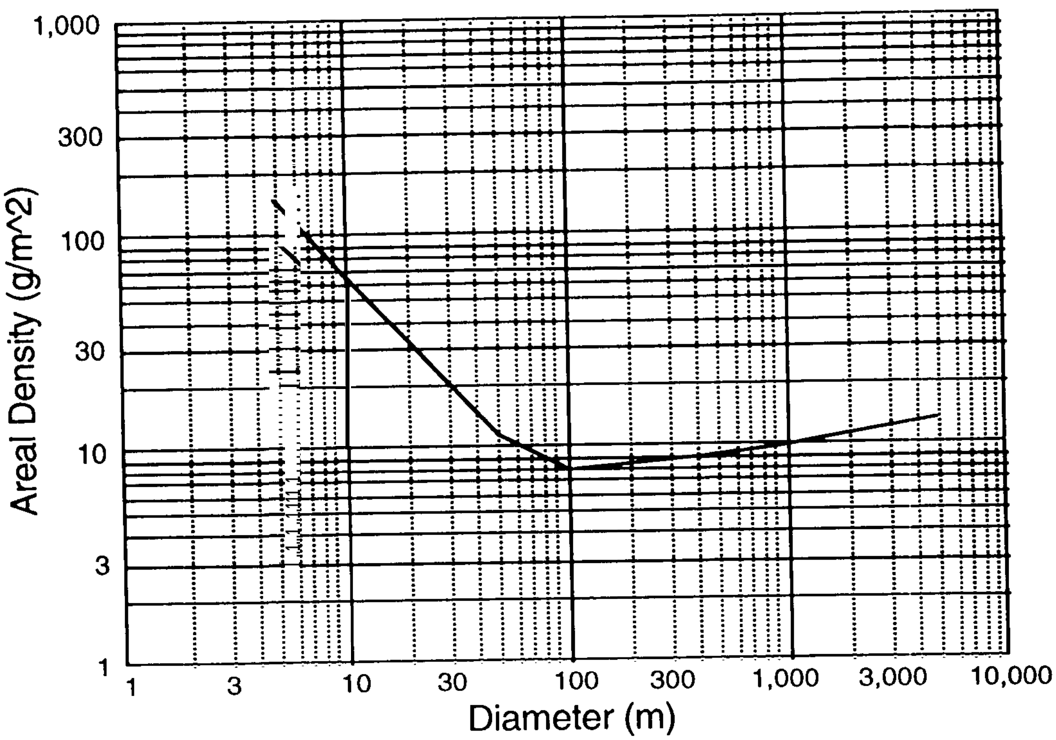

Figure 2. Projected Inflatable Solar Sail Areal Density versus Final Deployed Diameter (Ref. 6)

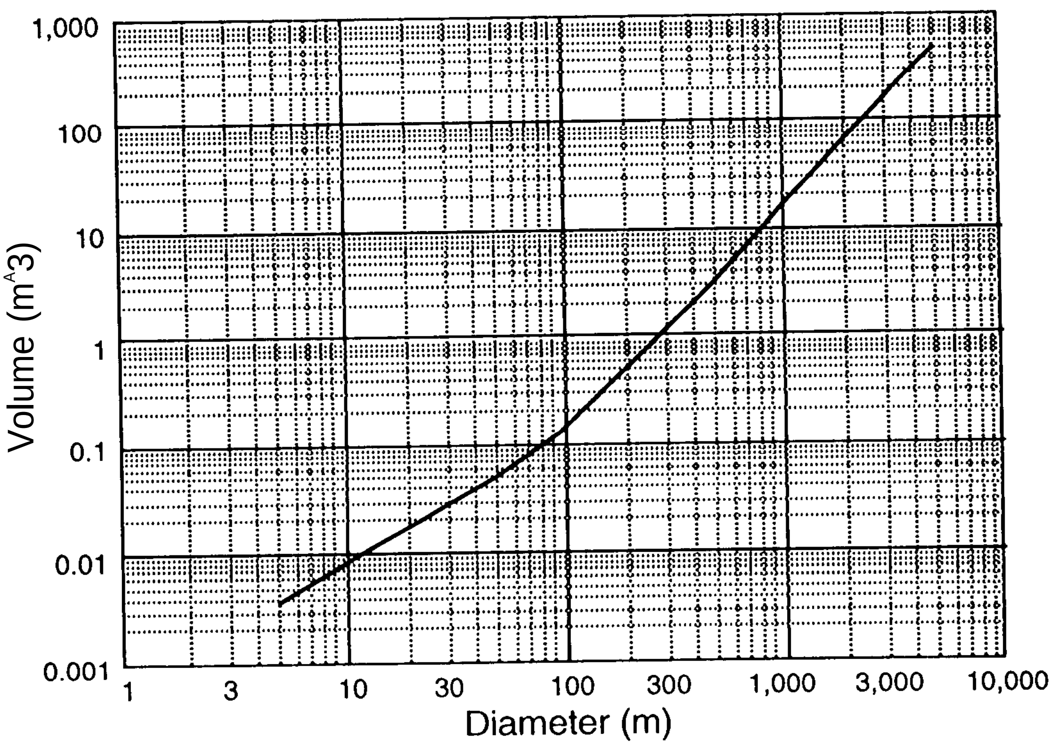

Figure 3. Projected Inflatable Solar Sail Launch Package Volume versus Final Deployed Diameter (Ref. 6)

is an important consideration for packaging the solar sail in a launch vehicle shroud. For inflatable solar sails with diameters on the order of 100 to 130 m, the packaged volume is expected to be less than about 0.2 m^3.

Solar Sail Trajectory Analyses

Low-thrust solar sail heliocentric trajectories were analyzed by Sauer.[8] The planetary escape and capture spirals were modeled after the method of Sands.9 The results are shown in Figure 4 (next page). The usual free parameter is the characteristic acceleration (A_c) of the loaded sail for the Earth-to-Mars trip. The characteristic acceleration of the sail is found by dividing the total "thrust" at 1 AU by the total mass of the sail including any payload (M_{PL}). The total "thrust" at 1 AU is thus:

$$\text{Thrust } [\mu N] = (\, 9\ \mu N/m^2\,) \bullet (\text{ Sail Area [m2] }) \bullet (\ 0.95\ \text{[Reflectivity]})$$

where the sail sheet is assumed to have a reflectivity of 95%. The sail mass (including payload, M_{PL}) is:

$$\text{Sail Mass} = (\text{ Area] Density } [g/m^2]\,) \bullet (\text{ Sail Area } [m^2]\,) + M_{PL}[g]$$

Finally, the characteristic acceleration is:

$$A_c[mm/s^2] = (\text{ Thrust } [\mu N]\,) / (\text{ Sail Mass [g] })$$

Given A_c, the trajectory analysis computer code calculates departure and arrival dates as well as the corresponding trip times. Note that values of A_c less than 0.6 mm/s^2 are not considered because this represents a lower limit for both the analysis codes as well as for maneuvering near a planet (e.g., there is not enough acceleration to turn the sail and re-orient it as it passes from shadow to light).

Launch Vehicle Performance

For these analyses, we have assumed the use of a Pegasus XL launch vehicle with a STAR 27 kick motor. This launch vehicle combination can inject 110 kg to a C3 of O km^2/s^2 (i.e., to just barely Earth escape) for a cost of \$20M to \$25M.[10] Note that by injecting to Earth escape, it is possible to avoid the long Earth-escape spiral (e.g., up to 1300 days) required when a solar sail is deployed in high Earth orbit (e.g., 2000-km altitude). As shown in Figure 5, it appears feasible to package the solar sail, payload, and STAR 27 kick stage within the available Pegasus XL launch shroud. Specifically, there is room for two 0.2-m3 cylindrical volumes (one for the sail and one for the payload) with dimensions of 76-cm diameter by 45-cm length. (However, a new payload adapter [PLA] would be required because the standard Pegasus adapters do not accommodate the dimensions of the STAR 27 motor.)

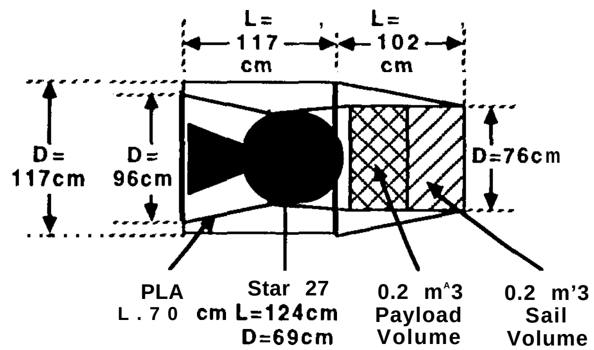

Figure 5. Pegasus Standard Launch Shroud Dimensions (Ref. 10)
(PLA = Payload Launch Adapter)

MISSION ANALYSIS RESULTS

For the mission analyses, we took the Pegasus XL/ STAR 27 injected mass(110 kg) and assumed a characteristic acceleration (A_c) ranging from of 0.6 to 1.0 mm/s^2. Given these values (and a solar pressure of 9 N/km^2 at 1 AU), we then calculated the corresponding sail area (with a reflectivity of 0.95). We then assumed a sail area] density ranging from 4 to 14 g/m^2, and calculated the solar sail mass and resulting net payload mass. The results are shown in Figures 6 and 7.

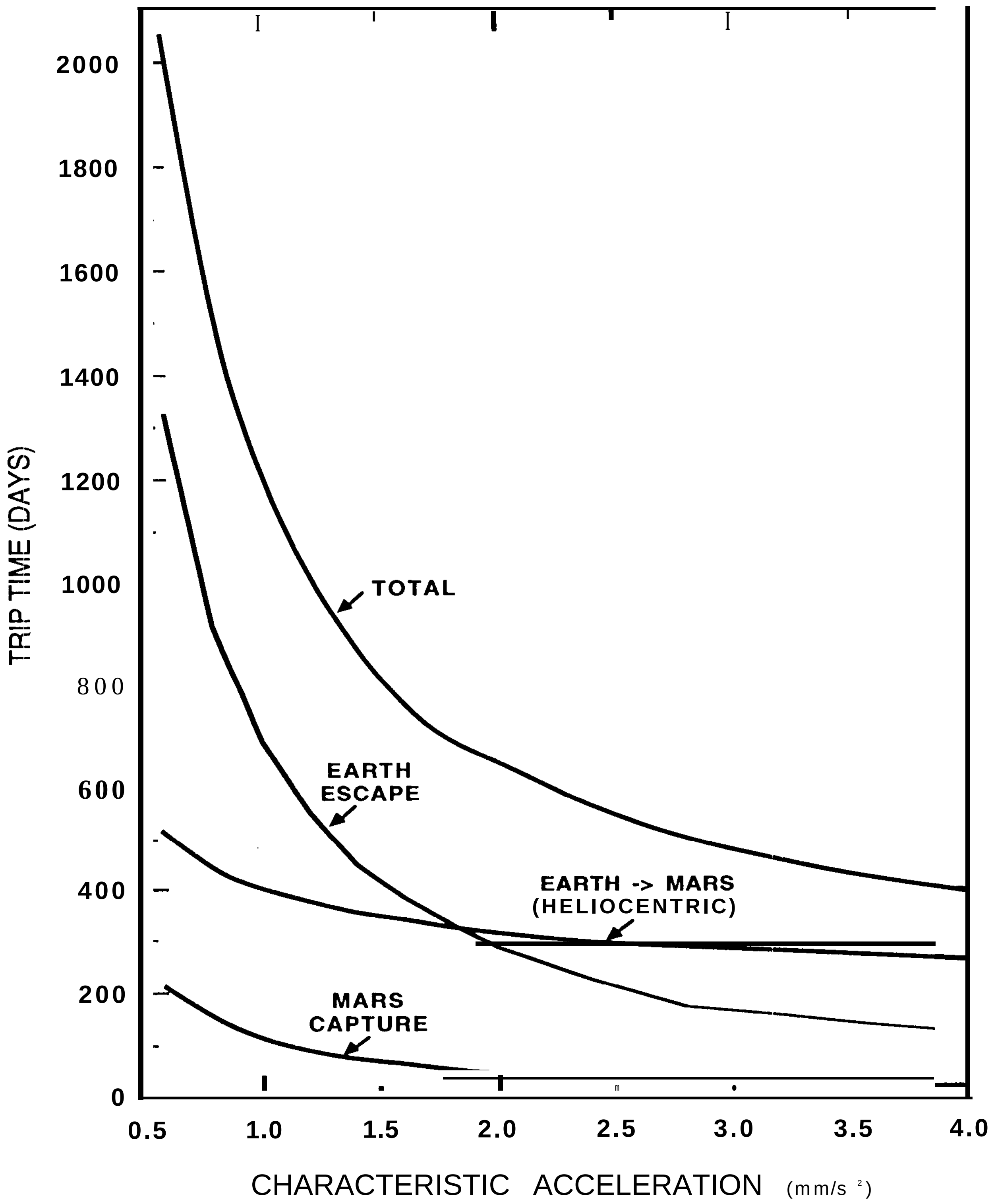

Figure 4. Solar Sail Earth-to-Mars Trip Time versus Characteristic Acceleration

Figure 6 illustrates the solar sail diameter (assuming a circular sail) as a function of trip time. (The corresponding edge length for a square sail is 0.886 that of the circular sail diameter.) The lowest characteristic acceleration assumed (0.6 mm/s^2) results in an Earth-to-Mars trip time of about 725 days, or about 2.8 times the minimum-energy (Hohmann) ballistic trip time (2.58 days). As mentioned above, using the launch vehicle to provide all of the Earth escape velocity eliminates the roughly 1300-day Earth escape spiral of the solar sail.

Interestingly, given the modest total mass of the vehicle (1 10 kg) and relatively low characteristic accelerations, the solar sail's size is quite reasonable, only on the order of 100 to 130 m. Thus, if acceptable areal densities can be achieved, the required sail dimensions can be met with inflatable optics system sizes proposed for relatively near-term applications.

Figure 7 shows the results of the calculations of net payload mass as a function of trip time (i.e., characteristic acceleration) and the solar sail areal density. Not surprisingly, the lower the areal density of the sail, the greater the payload mass that can be accommodated. Thus, for the areal density of a Halley Comet-class square solar sail (assuming that it would have the same 5 g/m^2 for dimensions of around 100 m rather than of kilometers), the payload mass can be almost 70 kg. What is remarkable is that for near-term inflatable optics dimensions and areal densities (i.e., 99-m diameter and 8-g/m^2 areal density), the payload can have a mass of 48 kg. Furthermore, even a conservative areal density (e.g., 12 g/m^2) can permit a potentially useful microspacecraft payload (e.g., 17 kg). Thus, there appears to be a significant opportunity for the near-term use of small, low-cost launch vehicles to support microspacecraft solar sail planetary exploration missions.

This potential benefit is especially noteworthy when we consider the alternative of using a chemical propulsion system for the same mission. In this case, the spacecraft chemical propulsion system must supply a total AV of 5.12 km/s, consisting of 2.95 km/s for C_3=0 to trans-Mars injection (C_3=8.68 km^2/s^2), 0.10 km/s for midcourse trajectory maneuvers, and 2.07 km/s for insertion into a 500-km altitude circular Mars orbit. For an I_{sp} of 310 lb_f-s/lb_m (3038 N-s/kg) typical of a bipropellant thruster, the initial 110-kg microspacecraft requires approximately 90 kg of propellant, leaving only 20 kg for the "dry" propulsion system and payload. Assuming a nominal "tankage factor" of 15% of the propellant mass as propulsion system "dry" mass leaves only 7 kg of net payload, or roughly one-seventh the payload delivered by the solar sail.

ISSUES NOT ADDRESSED

There are several issues that have not been addressed in this mission analysis. These include the need for inflatable solar sail attitude control, the potential for additional uses for the inflatable optics structure of the sail, and other mission applications.

Inflatable Solar Sail Attitude Control

As with the classic square solar sail configuration, an inflatable solar sail could use small, independently-articulated "fly swatter" vanes. These could be of conventional thin-film and boom construction, or inflatable structures. Alternatively, the sail could be maneuvered by shifting the payload so that the center of mass is offset from the center of (light) pressure. Either approach may introduce the need for mechanically-complex systems with an unacceptable mass or power requirement for the modest-size sails considered here. (By contrast, there was a significant economy-of-scale realized by the use of kilometer-sized classic sails; with their large areas, even relatively heavy systems **could** still yield an acceptable areal density.)

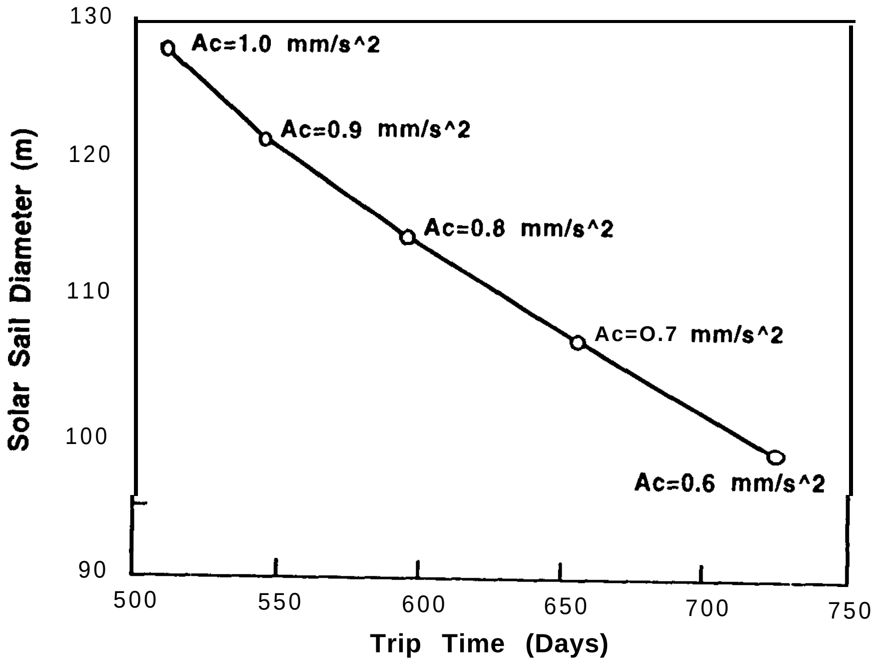

Figure 6. Solar Sail Diameter versus Earth-to-Mars Trip Time
(Earth-to-Mars Trip Time Includes Heliocentric Transfer and Mars-Orbit Capture)

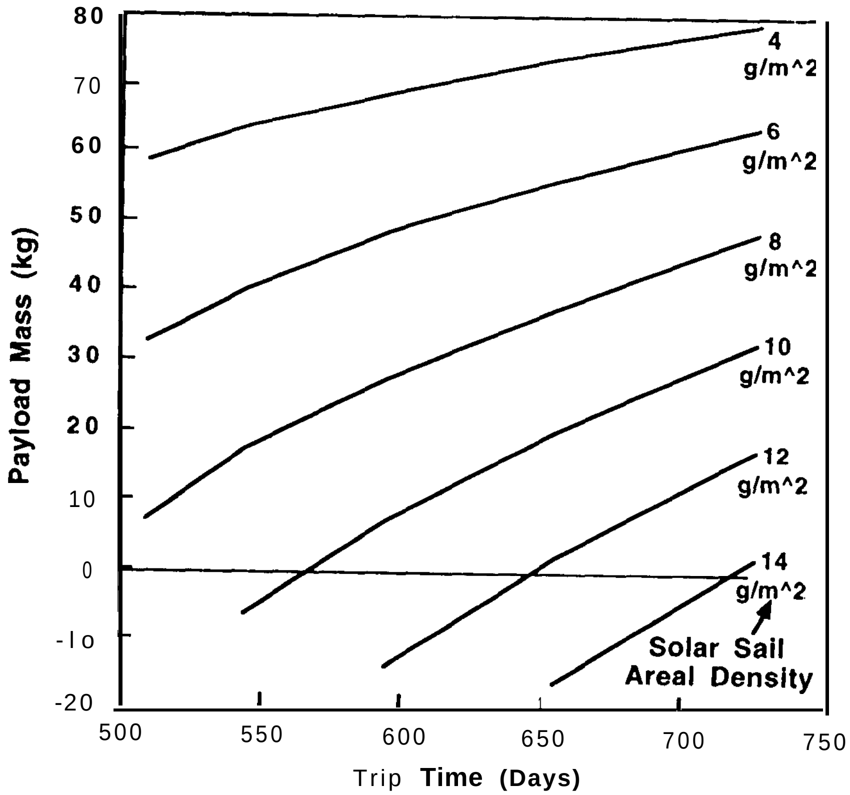

Figure 7. Net Payload Mass versus Earth-to-Mars Trip Time
(Earth-to-Mars Trip Time Includes Heliocentric Transfer and Mars-Orbit Capture)

Operational Synergisms with the Inflatable Optics Sail

As discussed previously, the inflatable solar sail concept is basically an inflatable optics system. Thus, we can imagine the microspacecraft using the sail as a high-gain antenna (assuming that a parabolic, rather than flat shape is used for the sail membrane). However, this might prove infeasible, because the sail would then reflect and focus sunlight onto the microspacecraft when the sail was pointed directly at the sun. For comparison, at Mars orbit (1.52 AU), the sunlight collected by even the smallest sail corresponds to almost 4.3 MW of solar energy. There may be some combination of mechanical schemes to make this possible; however, the added complexity (and mass) could easily outweigh any potential benefits.

We also mentioned the possibility of using the sail's aerodynamic drag to slowly aerobrake into a lower altitude and eventually de-orbit the spacecraft for landing (analogous to the orbit-changes performed by the Magellan spacecraft at Venus), At Earth, an initial deployment altitude of 2000 km is assumed so that air drag is significantly less than solar pressure (even in a "solar maximum" year when the atmosphere expands outward).[4] The corresponding altitude for Mars would need to be determined to assess the feasibility of this concept.

Other Mission Applications

A large variety of solar sail mission applications were identified during the JPL Halley Comet rendezvous mission studies;[1] these potential applications should be re-analyzed on the basis of the new inflatable solar sail and microspacecraft paradigm discussed in this paper.

SUMMARY

This analysis has shown that there is a significant potential synergism between the emerging technologies of microspacecraft and inflatable solar sails that offer the unique capability of performing planetary science missions using a small, low-cost launch vehicle, such as the Pegasus XL, with a launch cost of less than $25M. In the example evaluated here, a 100-m diameter inflatable solar sail can deliver a 48-kg microspacecraft payload to Mars orbit with a trip time of about 725 days. Once in orbit, the microspacecraft can perform orbit changes (including atmospheric entry) with no expenditure of propellant by using the solar sail.

This preliminary analysis has indicated the potential feasibility of this mission approach. Several issues remain which require further evaluation, including solar sail attitude control, operational synergisms (e.g., power production, communications, aerobraking, etc.), and other mission applications for inflatable solar sails and microspacecraft.

ACKNOWLEDGMENTS

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